Ballistic evaluation of flexible hard armour plates in bent and flat configurations

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Abstract. The growing recognition of the need for gender-specific protective equipment has highlighted the limitations of traditional rigid ballistic plates, particularly for female users. This emerging requirement has driven industry to develop innovative solutions to increase the fit and comfort of body armour, including high-curvature rigid plates and flexible hard armour. Flexible plates are designed to better conform to diverse body morphologies and offer increased comfort and mobility while maintaining the ballistic performance of traditional hard armour plates. Given the increasing availability of these technologies and the limited available data regarding their performance, various models of flexible plates were acquired with two objectives: 1) Adapt the ballistic test methodology to account for the new challenges posed by flexible hard armour, and 2) evaluate the ballistic performance of the acquired armour system. The plates were initially radiographed in their neutral state to establish a baseline. Subsequent bending tests revealed directional limitations in some models and a significant initial resistance that decreased with repeated flexions. This led to the development of a break-in procedure to simulate real-world usage. A second radiography series was then performed with the plates bent to match the NIJ 0101.07 applique shape. This was conducted to assess the impact of the break-in process on the plate's construction and integrity and identify potential vulnerabilities in the bent configuration. Finally, the plates were subjected to ballistic testing in the standalone condition against their specified threat in various bent configurations to evaluate their performance. While only a few complete penetrations were observed, the tests highlighted excessive backface deformation. Additional limited testing, however, suggests that using the plates in conjunction with other protective elements (e.g. as a system) may help mitigate backface deformation to a certain extent.

1. BACKGROUND

In recent years, there has been a growing requirement for body armour that can accommodate a more diverse population and a larger range of body morphologies. Flexible hard armour plates and body armour with higher curvature radii are becoming increasingly common on the market. The latest edition of the NIJ now includes test methodologies specifically tailored toward female body armour [1].

The increasing demand for inclusive ballistic plate armour has driven the industry to develop new solutions that enhance suitability and comfort for everyone. These solutions include a growing range of available sizes and shapes, such as the one in Figure 1 below.

Figure 1 : Example of inclusive hard armour plates on the market [2] [3]

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One of the first commercial flexible hard armour systems was *Dragon Skin*, proposed in 2007 by Pinnacle Armour. The system, shown in Figure 2, featured a unique design composed of overlapping ceramic discs arranged in a flexible scale-like pattern, resembling reptilian/fish skin [4].

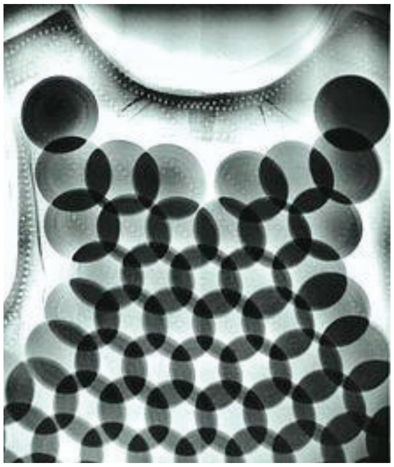

Figure 2 : X-ray of dragon skin body armour (adapted from Wikipedia)

Despite the commercial failure of the *Dragon Skin [4]*, new models of flexible hard armour systems seemingly meeting military performance requirements are now available. The added conformability of such designs accommodates various body types and hopes to enhance both comfort and mobility for users.

The increasing market availability of this technology, coupled with limited performance data, led the Department of National Defense to procure small quantities of various Commercial of the Shelf (COTS) systems with the goals to understand current technologies, investigate necessary adaptions to test methodologies and assess the performance of flexible plates compared to standard rigid plates. The levels of performance stated by the manufacturers for the product evaluated were level RF1 following the NIJ 0101.07 standard [1]. Some models were claimed to stop additional and more performant threats, such as the 7.62mm API-BZ.

2. METHOD

2.1 General observations of the technologies

The first notable difference is the thickness between standard rigid plates and flexible plates. For this level of performance, a modern plate thickness typically ranges between 19 to 25 mm. In this case, most models were around 22mm, but some were as thick as 29 and even 37mm. This difference in thickness can be explained by the level of performance of the plate and by its construction. Instead of relying on a monolithic ceramic design, all tested flexible plates used multiple tiles made of various materials and shapes (e.g. hexagonal) placed side by side in a mosaic structure (Figure 3) and bonded to semi-flexible composite backing, i.e. not consolidated. The flexible composite backing provides some shape conformability while maintaining the ability to stop projectiles. The overlapping of adjacent tiles for one particular system also contributed to making the flexible plate thicker.

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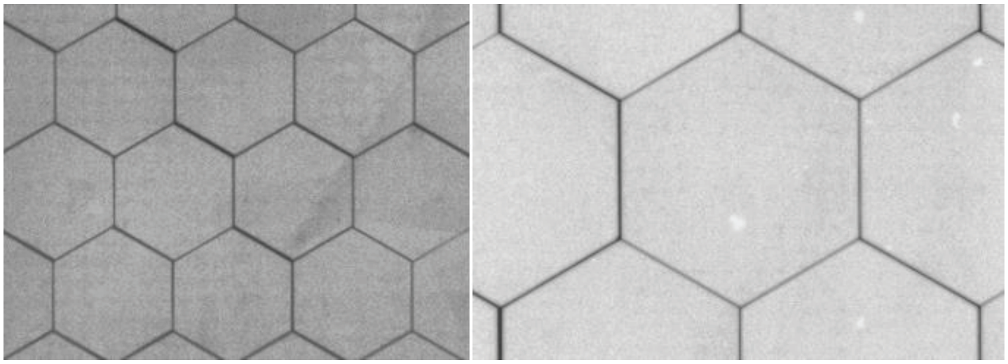

Figure 3 : Construction example of two different flexible plates seen through X-Ray. Both designs have the same scale.

Regarding areal density, the acquired plates ranged from 32 to 48 kg/m². These values were obtained based on the protected area of the plate in a neutral position (not bent) as opposed to the overall area. As a reference, a regular modern level 3 plate can have an areal density as low as 26 kg/m². The materials used in the construction of these plates have a significant influence on the areal density. For instance, the heaviest system used metallic tiles at the strike face instead of ceramic tiles. The data reveal a distinct trade-off, wherein gains in flexibility are counterbalanced by increases in both the mass and, occasionally, the thickness of the plates. This also shows the importance of human factor testing to assess how well this compromise performs in practice.

2.2 Radiography & Break-in

Radiography was used to determine if bending the plates might create vulnerabilities at the intersection between tiles. These vulnerabilities would then be exploited during the ballistic test. For this purpose, a low-density foam shaped in accordance with NIJ 0101.07 C-5 standards [1] was used to bend the flexible plates in the same manner as they would during ballistic testing. An example of a plate positioned in front of the X-ray tube is shown in Figure 4. In most cases, bending the plate separated the tiles over one or two rows near the breast region, as shown in Figure 5.

Figure 4 : NIJ 0101.07 C-5 Shape foam for radiography

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Figure 6 shows the significant differences in curvature between the NIJ C-5 female applique and the standard SAPI profile.

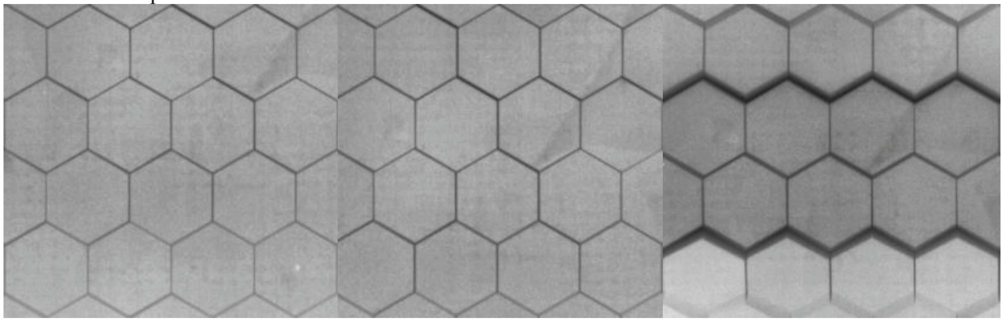

Figure 5 : Tiles before break-in (left), after break-in (middle) and bent on the C-5 applique (Right).

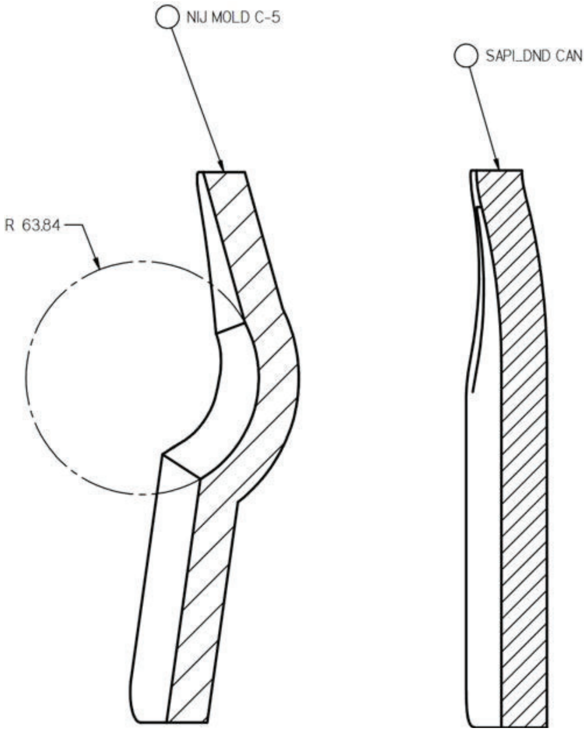

Figure 6 : Curvature difference between the NIJ C-5 and the SAPI plate

The construction and the material used to assemble these plates also affect their flexibility. Some models offer flexibility in both directions simultaneously, while others can only be bent in one direction. It also became apparent that the initial bending resistance decreased significantly with repeated flexion. Therefore, before proceeding with a ballistic test, all plates underwent a break-in process where they were manually bent in the vertical plane several times until the force required decreased and stabilized. Approximately 30 cycles were necessary for each plate to get to this point.

Radiographies were taken before and after this break-in procedure to determine if it had any adverse effect on the position and bonding of the tiles. Minimal to no differences were observed due to the break-in process, as seen in Figure 5.

2.3 Ballistic Test

Following the break-in process, the plates were directly tested without performing any additional conditioning (e.g., drop, temperature cycling, humidity) and following the NIJ test procedures [1]. Prior to testing, plates were conditioned for at least 12 hours at an ambient room temperature of 20±3°C.

ROMA Plastilina No.1 modelling clay was used as the backing material for all tests. The clay was calibrated using the standardized drop-weight technique. A 457 x 406 x 102 mm rigid metallic clay box was used for all tests. For the medium-size plates, the clay backing was shaped in accordance with the SAPI shape, and the NIJ C-5 female applique since the majority of the acquired plates were medium sizes (e.g. 25x 30 cm) in a SAPI shooter's cut profile. For the plate of a smaller size (20x25 cm), the NIJ C1 female applique was used to shape the clay backing. During testing, the plates were successively mounted and bent on the SAPI-shaped clay backing and on the higher curvature NIJ C-1 /C-5 shaped backings (Figure 7), which is referred to as the flex shape designed for testing female soft armours. The plates were all tested in the standalone configuration (e.g. without any soft armour insert behind) except for one plate, which was tested in conjunction with an aramid soft-body armour insert with an areal density of 3.3 kg/m^2. The detailed test matrix is provided in Table 1.

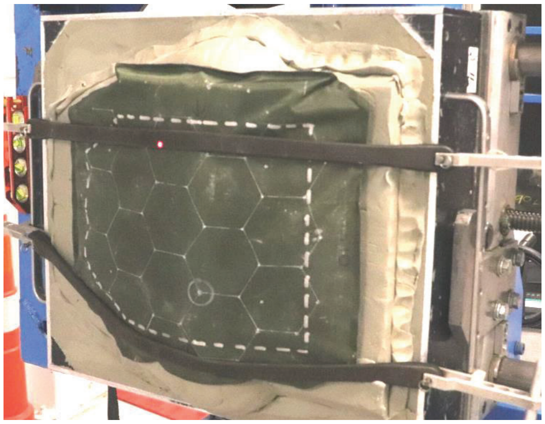

Figure 7 : Flexible Plate mounted on NIJ C-5 clay applique.

In contrast to NIJ 0101-07 [1], the target support for each plate was adjusted to produce normal impacts with a zero-degree obliquity angle. Velocity measurement was done using two independent Doppler radar. Yaw was measured within 150 mm of the impact point using two high-speed orthogonal cameras. To be considered fair, the maximum velocity deviation was ±10m/s, and the maximum acceptable yaw was 5°. Two custom shot patterns were defined for the ballistic tests. For the 7.62 mm rounds, 4 rounds were fired in a 120mm ±15mm square/diamond shooting pattern, and for the 5.56mm rounds, 6 rounds were fired in two triangle configurations, as shown in Figure 8. No shots were made within a 25 mm wide exclusion zone around the plate to minimize edge effects. Triple points and weak areas were targeted as frequently as possible for the SAPI-shaped configuration. For the flex configuration, the shot patterns were adjusted to incorporate as many shots as possible in the areas with the largest inter-tile separations due to bending.

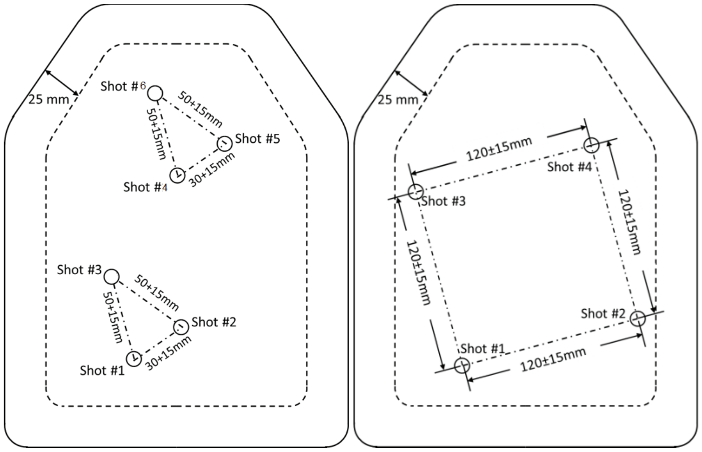

Figure 8: Shooting patterns for the 5.56 mm on the left and the 7.62 mm on the right.

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2.4 Threats

Three different threats were used to test the acquired plates, as described below and illustrated in Figure 9.

2.4.1- 5.56mm C77

This is the Canadian version of the M855 or SS109. This is a 4.0±0.1 grams (61.8±1.5 grain) full metal jacket bullet composed of a lead and steel core. Its test velocity is 950 m/s. This threat is equivalent to the RF2 level as per NIJ 0101-07 [1].

2.4.2 – 7.62mm C21

The C21 is the Canadian version of the M80. This is a 9.5±0.2 grams (147±3 grain) full metal jacket ball round with a lead core and a copper jacket. Its test velocity is 847 m/s. This threat is equivalent to the RF1 level as per NIJ 0101-07 [1] or level III as per NIJ 0101-06 [5].

2.4.3– 7.62mm API-BZ Surrogate

The API-BZ projectile, used for this test series, is a Canadian surrogate developed by DRDC to match the ballistic penetration performance of the original Russian round as per VPAM level 8 [6]. It is a 7.70 grams (118.8 grain) bullet with a test velocity of 740 m/s. Only plates that were rated for this level were tested against it.

Figure 9 : 5.56mm Canadian C77 (Left), 7.62mm Canadian C21 (middle) and 7.62mm API-BZ Surrogate (Right).

3. RESULTS

A total of 116 shots were fired against the 25 flexible plates acquired for this project. Among those 25 plates, six (6) different systems were tested against the three threats from section 2.3.4 in both the SAPI and the flex configuration, as shown in Table 1 below.

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Table 1 : Test Matrix

Plate model	AD (kg/m²)	Level	Construction	Config	Backing	Threat	Nb plates	Shots on tile	Shots on gap
M1	47.9	NJI 06 III+	1.2 in^2 hexagonal SiC mosaic tiles	Flex	C5	C21	1	2	2
						C77	1	1	5
				SAPI	SAPI	C21	1	4	0
						C77	1	3	3
						API-BZ	1	1	3
M2	45.9	NIJ 06 III	4.8 in^2 hexagonal Titanium mosaic tiles	Flex	C5	C21	1	2	2
						C77	1	3	3
				SAPI	SAPI	C21	1	3	1
						C77	1	5	1
M3	35.4	NIJ 06 III	3.9 in^2 hexagonal B4C overlapping mosaic tiles	Flex	C5	C21	1	3	1
						C77	1	3	3
				SAPI	SAPI	C21	1	4	0
						C77	1	6	0
M4	32.1	NIJ 06 III	1.37 in^2 hexagonal Alumina mosaic tiles	Flex	C1	C21	1	1	2
						C77	1	1	3
				SAPI	SAPI	C21	1	2	1
						C77	1	4	2
M5	36.7	NIJ 06 III	1.2 in^2 hexagonal Alumina mosaic tiles	Flex	C5	C21	1	2	2
						C77	1	2	4
				SAPI	SAPI	C21	1	3	1
M6	40.6	NJI 06 III+	1.2 in^2 hexagonal Alumina mosaic tiles	Flex	C5	C21	1	2	2
				SAPI	SAPI	C21	1	3	1
						C77	1	4	2
						API-BZ	1	2	2
M6 In conjunction				SAPI	SAPI	C21	1	2	2

Of the 116 shots, 11 were Complete Penetrations (CP), meaning that the bullet was able to defeat the plate. While the data is limited, there was no indication that shooting in a gap/weak area increased the probability of perforation, as shown in Table 2. From the two plate models (M1 and M6) rated to stop the API-BZ (i.e., VPAM level 8), only the flexible plate model M1 stopped the four projectile impacts. All three CPs with this threat were on the M6 plate model, as shown in Table 2.

Table 2 : **Number of complete penetrations per configuration**

Threat	Plate Model	Flex		SAPI	
		Gap	Tile	Gap	Tile
7.62 mm API/BZ	M1				
	M6			1	2
7.62 mm C21 (M80)	M1				
	M2	1	1		1
	M3				
	M4				
	M5				
	M6				
	M6 in conjunction				
5.56 mm C77 (SS109)	M1			1	
	M2	1			2
	M3				1
	M4				
	M5				
	M6				

The multi-hit ballistic resistance of the acquired flexible plate systems was quite different between the six (6) plate models tested. As mentioned previously, the construction of the different systems is very different from one to the next. Some models use smaller hexagonal ceramic tiles arranged in a mosaic pattern. Tests showed that a single impact on one tile can cause surrounding tiles to shatter into dust, leaving a larger area vulnerable to subsequent impacts. Conversely, other models that used larger metallic tiles, confined impact damage closer to the strike zone while preserving the rest of the plate.

In terms of backface signature (BFS), the C21 (M80), with its high mass and lead core, caused a significant deficiency, with most models having BFS above the 44mm threshold. These failures were unexpected since all plates were claimed to be NIJ-compliant. Table 3 shows similar BFS values in the SAPI and flex configurations, suggesting that the level of plate bending is not a factor that impacts the BFS mitigation performance.

Table 3 : **Average backface signature (mm) per model against the 7.62mm C21.**

Plate Model	Flex		SAPI	
	Gap	Tile	Gap	Tile
M1	43.7	43.1		43.8
M2	47.5	49.8	48.7	51.0
M5	41.7	42.7		43.9
M4	66.9	61.0	62.6	57.1
M3	56.0	51.8	53.2	52.6
M6	51.6	47.5	47.8	50.9
M6 in conjunction			42.7	44.5

Given that the BFS values obtained were above the 44mm threshold, it was decided to assess the performance of a given system in conjunction with a soft body armour insert, which is representative of realistic operational scenario. To this end, the M6 plate model was also tested in conjunction with an

NIJ level 2 soft body armour insert. This arrangement resulted in an average BFS reduction of 13%, as shown in Figure 10, making it almost NIJ compliant.

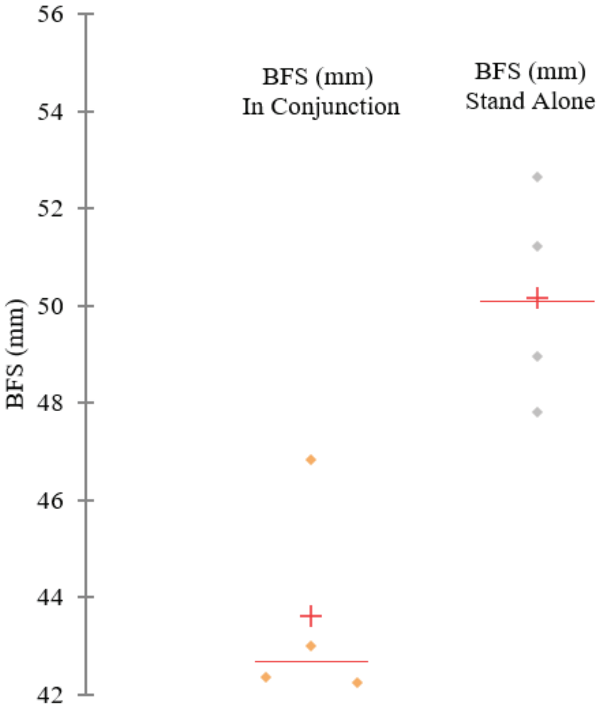

Figure 10 : BFS comparison with and without soft body armour

4. CONCLUSION

One hundred sixteen (116) individual tests were performed on six (6) different flexible systems, offering only a broad assessment of COTS flexible plate ballistic performance. Additional sampling and testing would enhance the reliability of the observations made in this paper. The results indicate that plate conformability, which should increase user comfort and broader morphology accommodation, might come at the cost of thicker and heavier designs and reduced ballistic performance, particularly regarding BFS. Nonetheless, this added flexibility does not seem to create weakness between joints. Multi-hit ballistic performance requirements for flexible systems will need to be defined in more detail in future purchase descriptions and body armour standards, given the large, damaged areas around the impact points on some of the systems tested. Additional testing could demonstrate if the break in procedure impacts performance which could lead to the development of a standardized break in procedure. A tensile machine could potentially be used to perform the break-in a uniform and repeatable manner.

Future testing would benefit from evaluating Vproof and BFS separately. BFS measurements should be conducted with a plate well supported by clay, while Vproof testing could be performed on a ballistic gel torso model that better represents the male and female human body shapes. This approach would provide more realistic boundary conditions where an air gap between the plate and the human body might exist, especially for female users. Additionally, it could be valuable to scan through X-ray or Tomography the plate following each impact. This would provide crucial information on the point of impact and damage to adjacent tiles which in turn, could provide a better understanding of the failure mechanisms. This knowledge could contribute to the development of more robust and reliable flexible armour solutions.

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